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SYNOPSIS OF DRAG REDUCTION IN NATURE

D. M. Bushnell
Head, Viscous Flow Branch
High-Speed Aerodynamics Division
NASA Langley Research Center, Hampton, Virginia

K. J. Moore
President
Cortana Corporation
Falls Church, Virginia

Introduction

The "energy crisis" of the 1970's rekindled interest and research in drag reduction techniques for all types of transportation; land, sea, and air. As in any research, the kernel problem for drag reduction is the genesis and development of new approaches, techniques, insights, and understanding. One source of inspiration for alternative drag reduction approaches is a renewed study of Avians and Nektons, i.e., fliers and swimmers in the natural world. The presumption is that drag reduction adaptations have evolved for improved efficiency or speed, or both; thereby aiding species survival in the Darwinian sense. Such a study should result in (a) identification of approaches which technology could pursue and, if successful, optimize for practical application; (b) identification of instances where existing human-derived technology occurs in the natural world; and (c) improved understanding of animal form and function. The present article documents the current status of such an examination pursued intermittently over the last 10 years by the authors for ultimate application to such systems as aircraft, submersibles, surface ships, and long-distance pipelines.

An appropriate beginning is to define and delineate the various forms of drag affecting both natural and man-made fliers and swimmers. Potentially the largest drag component is pressure or form drag which is particularly troublesome

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when flow separation occurs. The basic physics for this drag component involves the viscous influence upon the ideal or inviscid flow pressure field. Some pressure drag, of a relatively benign level, occurs even if the flow is attached, simply due to the uncambering of the surface by viscous-induced flow displacement. However, once flow separation occurs this drag component increases tremendously. Therefore, the foremost consideration for drag control and mitigation for species survival and efficiency is probably the avoidance of flow separation. The two remaining drag components (for submerged swimmers and fliers), skin-friction drag and drag-due-to-lift, are usually of the same order and much smaller than the pressure or form-drag component, except in the attached flow case. Skin-friction drag is the result of the no-slip boundary condition on the surface and can be either laminar (low drag, low Reynolds number) or turbulent (high drag, high Reynolds number). In fact, the maintenance of laminar flow to higher Reynolds numbers is an obvious, and currently much in vogue (again), technique for obtaining skin-friction reduction. The various drag mechanisms are not independent and, as the laminar case is more easily separated, it may be advantageous to artifically trip the flow turbulent to avoid the large pressure drag penalty associated with separated flow. The remaining drag component, drag-due-to-lift, is caused by flow spillage on lifting surfaces from high to low pressure regions and affects both fliers, which require lift to remain in the air, and swimmers, many of which utilize "lifting surfaces" for propulsion and control.

The bulk of the drag reduction techniques identified thus far in the natural world are discussed in the present article under their appropriate heading, e.g., (1) Form Drag Reduction, (2) Skin-Friction Drag Reduction, and (3) Drag-Due-to-Lift Reduction, so the reader can gain an appreciation for the diversity of "natural" drag reduction. As stated previously, these techniques can often be utilized for either improved cruise efficiency or increased speed, depending upon the ecological niche occupied by the species. Three classes of drag reduction approaches are described: (a) those that have proven performance potential, i.e., careful human research demonstrates that the method "works"; (b) approaches for which only preliminary data exists and therefore are only tentative; and (c) morphological observations which, in the opinion of the present authors, are worth further scientific study to determine their efficacy.

Form-Drag Reduction

The fundamental problem in form-drag reduction is to avoid flow separation, both steady and unsteady (vortex shedding), for three-dimensional flows. The three-dimensional specification is important as there are few if any two-dimensional or truly axisymmetric creatures or creature parts in nature, although close approximations are common in human technology. Flow separation (flow breakaway from the surface) is induced by positive or adverse pressure gradients, i.e., pressure fields where pressure increases in the streamwise direction. Typically, the forward portion of the body is a region of falling pressure, while the after portion is subject to increasing pressure. Therefore, afterbody regions are the most prone to flow separation, albeit perhaps less so for the three-dimensional "natural" bodies prevalent for Nektons and Avians as compared to the two-dimensional and axisymmetric bodies often favored in human technology. Flow separation occurs due to a lack of flow momentum near the surface sufficient to overcome the increasing pressure. The local flow far from the surface contains higher momentum, and the cononical flow separation control/pressure drag-reduction problem is to transfer momentum toward the wall region from the outer flow.

Turbulent flow - As stated in the introduction, laminar flows are much more separation-prone than the turbulent case, where dynamic eddying motions cause outer-to-inner (near wall) region momentum transfer which can delay separation. Therefore, one form of flow separation control is the establishment of turbulent wall flow. Adverse pressure gradients themselves constitute a major turbulizing factor on the flow but in addition several species deploy roughness, using either projecting bands near the position of maximum body girth (e.g., Refs. 1-4) or embedded (and unstable) separated flow regions (such as on the dragonfly wing, Ref. 5), presumably to ensure the presence of turbulent flow over the afterbody. This particular ploy is only usable in cases where (a) the forward portion of the animal is kept smooth and laminar for low drag (Ref. 3) and (b) the Reynolds number (ratio of dynamic to viscous forces) is large enough to allow turbulence production using "trips" (geometric irregularities). The efflux from fishgills, positioned near the maximum girth, may also provide a turbulence enhancement function (Ref. 6), as could the mass addition from subdermal canals and passive porous surfaces (Refs. 7,8) and feather porosity-induced surface bleed. For the fully laminar lower Reynolds number case, the "natural" approach of choice for pressure drag reduction is "design" for reduced pressure gradient, i.e., longer, more gradual afterbody region (e.g., Ref. 3), or use of auxiliary body features to exploit favorable interference, such as the alula near the leading edge of bird wings (Refs. 9 and 10, similar to the leading-edge slot utilized on aircraft). Turbulization of the caudal or propulsive fin is probably hastened by the small scale turbulence shed by the caudal finlets due to swimming body motions (Ref. 3).

Vortex generators - An alternative approach for transferring momentum toward the wall for flow separation control is the establishment of "stationary" longitudinal vortex motions. Such "vortex generators" were "discovered" in the laboratory and researched in the 1940s and 1950s and are utilized extensively and routinely in human fluid flow technology. Their appearance in nature considerably antedates their human discovery. Vortex generator realizations in the natural world include the owl leading-edge comb (Refs. 9 and 11), certain bird feathers which "pop-up" under critical loading (Ref. 10) and shark dermal denticles and other scales which deform differentially upon body motion (Refs. 12 and 13), and the small separately set finlets behind the second dorsal and anal fins on many fast-swimming fish (Refs. 2, 3, and 14). For three-dimensional bodies and/or angle of attack, large scale nose-region induced vortices can control leeside separated flows and fighter aircraft designers are adapting the "shark nose" configuration as a result of studies which indicate that this nose shape produces vortices which are much more effective in separation control than "conventional" axisymmetric noses. Large surface grooves, both longitudinal and transverse, have also proven successful in reducing flow separation through vortex production and alteration (Ref. 15). Studies at NASA Langley of typical cactus shapes indicate sizable pressure drag reductions from alteration of the well known Karman vortex street by the transverse body grooves. Examples of longitudinal body grooves in the natural world include shell indentations (Ref. 16). These two cases, cactus and shells, are examples of organisms which, while being quite stationary, still "live fast," i.e., cactia in high desert windstorms and shells in underwater currents in the benthic boundary layer. Leaf deformation to minimize drag in high winds falls under the same catagory. As a final note under the heading of "Vortex Generators," swimming body motions can locally induce dynamic favorable pressure gradients (along with vortices) which can both delay separation and reduce turbulence production.

Mass Transfer - Another alternative approach to "energizing" the near-wall flow to obviate separation drag is to simply add momentum directly by blowing at high speed along the wall. This is again widely used in industry and is utilized in nature by fish which close down the inboard gill during turns and shunt the gill efflux into the outboard, separation prone, region of the body (Ref. 17). The orientation and placement of the gill openings are particularly well suited to this jet blowing technique, (Ref. 18) which is at the heart of much of the high-lift aviation technology. An alternative mass transfer technique is passive "bleed" or utilization of porous surfaces and subdermal channels in combination with the body/wing pressure field to remove the inner (near wall) low momentum region of the flow in separation prime regions (Refs. 7 and 8).

Adaptations for body intersection regions - This section describes adaptations for handling more localized flow separation control problems engendered by body-appendage intersections. The pressure field associated with intersection regions typically produces a horseshoe or necklace vortex which wraps around the base of the appendage (wing, fin, etc.) and streams back along the body. This vortex usually constitutes a net drag increase as, in this case, it is not generally employed to control an even larger separated flow region. A further separation drag problem with appendages occurs during maneuvering when the intersecting body is no longer alinged with the flow and therefore tends to create and shed large separated flows. Natural adaptations for drag mitigation in intersection regions reduce the causative transverse pressure gradients and include (1) filleting; (2) sweeping, often in a far better and more sophisticated manner than current practice in man-made technology; (3) elastic deformation to achieve optimum shape (Ref. 19); and (4) concentration of mucin-producing cells (Ref. 20). Details of these natural "fairings" have been little studied and such research could yield very valuable insight into passive techniques for three-dimensional vortex control. Intersection separation induced by angle-of-yaw/manuevering is approached through variable geometry, in the shark case the rear portion of the appendage near the surface flaps to the side as the body is moved providing a "turning vane" to guide the flow. An adaptation about which there is current speculation are the caudal finlets and keels which occur near the caudal fin-body intersection. Along with providing muscle attachments for side-to-side movement of the caudal fin, these keel appendages rotate the major body axis 90° (from "vertical" to "horizontal") and may thereby promote attached flow over the caudal fin. The flow field associated with caudal keels also requires considerable further study. The caudal finlets along the margin of the body probably serve to segment the organized vorticity shed by the body due to swimming motions and, when in pairs, accelerate the flow into the caudal (propulsive) fin (Ref. 2). One of the most obvious methods of dealing with protuberance drag is to eliminate the protuberance, and this is accomplished on some species by folding back various fins into the body at high speed (Refs. 3, 6, and 21).

Friction Drag Reduction

Skin-friction drag reduction is accomplished in nature through two basic approaches: (a) maintenance of laminar (low drag) flow as long as possible through use of smooth surfaces and favorable pressure gradients, and/or (b) body smoothness/alteration of the structure of turbulent motions once the near-wall flow becomes turbulent. Obviously decreasing the skin friction by large amounts in the presence of adverse pressure gradients is inadvisable, as this would invite flow separation and attendent large drag increases. Much of the skin-friction reduction technology identified thus far in the natural world is for the underwater case.

Surface "Additives" - Except for maintenance of laminar flow, surface additives provide the largest skin-friction drag reduction payoff in water. These additives are of three types: (a) polymers, (b) surfactants, and (c) bubbles. Detailed studies indicate that most fish slimes exhibit significant drag-reduction behavior (Refs. 22 and 23) with maximum effectiveness occurring upon deposition into the very near-wall region. Drag reductions well above 50 percent are commonly measured for the polymer case (Ref. 24). The appearance of ctenoid scales in the turbulent flow (and usually only the turbulent flow) regions of fish (Refs. 3 and 25) suggests that the tooth-like structure of these scales may aid in the deposition of the slime-polymer into the critical near-wall region. These "teeth" are a sub-roughness and therefore should not, by themselves, affect the turbulence directly. Also of interest in connection with polymer/slime is an apparent antifouling action which precludes formation of drag/roughness increasing marine growth (Ref. 26). It should be pointed out that while fish slime does contain high molecular polymer compounds, such as mucupoly-saccharides, nucleic acids, and proteins (Ref. 25), they also contain surfactants in the form of lipids, phospholipids, and lipoproteins (Refs. 27-30). It is only recently that surfactants were recognized as producing drag-reduction effects similar to aqueous solutions of polymer. While optimum concentrations of drag-reducing surfactants are generally higher than those for polymers, surfactants are more robust and do not exhibit the fractionation or mechanical degradation of the molecular complex exhibited by high molecular weight polymers.

The other additive, bubbles, decrease the average density near the wall and careful laboratory studies again indicate drag reductions above 50 percent. Both the polymer and bubble mechanisms are unique to water applications. In the air case, all gases are approximately Newtonian, and there is no injectable substance readily available which has a much smaller density. The use of bubble-drag reduction in nature is still speculative and concerns sailfish, seals, and penguins, where travel near and through the air-water interface could trap air within body surface layers which is observed to "outgas" from the surface in bubble form (Ref. 31). This is tenuous, as the bubble sheet is neither massive nor continuous as required in the laboratory experiments with man-made devices.

Morphology - Considerabley smallar O(10%) but still interesting levels of skin-friction reduction are available from surface and body-geometry modifications. Laboratory studies in the USSR indicate that the swordfish sword serves as a drag-reducing device (Refs. 3 and 32). The mechanism involves establishment of turbulent flow on the sword itself through special roughness provided by terbercles, folds, and spinelets (Ref. 33), and takes advantage of the fact that skin friction decreases as the viscous or boundary layer thickens on the body along the flow direction. In the swordfish case, the high drag associated with early/thin turbulent layers occurs on the sword, which has a small wetted area and hence a small total drag. By the time the turbulent flow reaches the main body of the animal the viscous layer is thick and therefore the drag per unit area is smaller over the main body region, which contains the major portion of wetted surface.

Another geometrical alteration associated with friction drag reduction is the ridge feature occurring on shark dermal denticles (Refs. 25, and 34-37). These ridges are lined up with the flow and are of a size and shape similar to the NASA "riblets" (Ref. 38) utilized on the 12M yacht, Stars and Stripes, in the 1987 America's Cup finals in Australia and in crew races in the recent olympics.

Drag-Due-to-Lift Reduction

Historically, drag-due-to-lift reduction in nature has been studied far less than either pressure or friction-drag reduction, and even then mostly for the avian/air case. This is curious, as studies identify this drag component as generally of greater import than friction drag (Ref. 39). The basic problem in drag-due-to-lift reduction is to either make use of, or reduce, the bleed flow which occurs from the high to low pressure regions of a lifting surface. The first and obvious ploy is to increase the span to chord ratio ("aspect ratio") of the lifting surface, as this makes the tip flow less and less important in the overall dynamics. Such an approach is limited by structure/strength of materials considerations but is employed to the extent possible (e.g., albatross wing aspect ratio ~ 17, Ref. 40). Other well documented "natural" drag-due-to-lift reduction techniques include the use of tip sails or tip feathers to segment the vortex which occurs at the tip due to the high to low pressure bleed (e.g., Refs. 41 and 42). The general concept is to "utilize" the angled tip flow by deploying embedded surfaces (split tips) which supply a thrust component from their lift vector. These tip feathers are used for example on the condor, evidently in lieu of larger aspect ratio, and are also useful in partially "blocking" the wing-tip bleed. The other reduction technique studied extensively is wing upsweep (Ref. 43).

More recently, various underwater creatures have been re-examined for morphological features possibly associated with drag-due-to-lift reduction. This has resulted in several new avenues of research and some early successes. The initial observations involved qualitative comparisons of caudal fin geometry as a function of structural makeup. In general, as one proceeds from bone (fish) to an exoskeleton (sharks) and finally to simple muscle (whale), the caudal fin aspect ratio tends to become (understandably from a structural point of view) smaller, but the fin itself tends to be more geometrically complex. The supposition was that the various morphological complexities may tend to compensate for the reduction in aspect ratio. Specific features identified for laboratory study included (a) swept-back tapered tips (which also occur on birds); (b) serrated trailing edges, both local near the tip (shark) and along the entire trailing edge (humpback whale, also many birds); (c) leading-edge bumps (pectoral fin on humpback whale, head on hammerhead shark); and (d) "fin rays" or wavy flow-aligned surface relief, including the optimal alignment of denticles near the tip. These features are listed in decreasing order of research attention received thus far. The swept-back tapered tips evidently do reduce drag-due-to-lift, at least partially due to a vertical distribution of the lift vector (Refs. 44-46). Tests at NASA Langley indicate the order of 10 percent reduction from serrated trailing edges, but as yet theoretical justification is lacking, due to the complex nature of the flow. The fin rays and leading-edge bumps are, up to this point, unexamined. Limited data (Ref. 47) indicate that spanwise gradients, such as those induced by such bumps, can alter stagnation point placement, rotate the lift vector into the thrust direction, and lead to drag reduction. The shark tip is paticlularly interesting as the outboard portion of the indentation evidently flips from side-to-side during caudal fin motions thereby forming a combination "winglet" and serration.

Viable drag-due-to-lift reduction techniques are of utmost importance in aircraft applications. Research over the last 10 years on skin-friction reduction (laminar flow control on wings, turbulent skin-friction reduction for fuselages) has yielded flight-verified, drag-reduction techniques capable of reducing overall friction drag up to 0(40%). However, since conventional aircraft optimize near the friction drag _ drag-due-to-lift condition, full utilization of this friction drag-reduction technology may not be possible without concomitant reductions in drag-due-to-lift, hence the interest in candidate "natural" drag- due-to-lift devices. Success in this area, in combination with the skin-friction reduction research already underway, should result in multi-billion dollar yearly fuel savings.

Status of Porpoise Drag Reduction

The present authors, when speaking on the subject of drag reduction in nature, are invariably queried concerning dolphin drag reduction. This wide public interest in the dolphin case evidently results primarily from a combination of "Grey's Paradox" and the "compliant wall" literature of the '50's and '60's. Sir James Grey, in the late '30's suggested, based upon energetics (steady-state energy balance), that the drag of various underwater creatures, including the dolphin, had to be inordinately low to correspond to speed claims (Ref. 48). This was followed in the '50's by an article by Max Kramer claiming that the "compliant" dolphin skin damped turbulent motions (Ref. 49).

Research conducted in the U.S. and the Soviet Union since the Kramer article has considerably clarified the situation. The Soviets have published (a) fluctuation measurements obtained in the boundary layer of a free-swimming dolphin and telemetered back to a shore station (Refs. 50 and 51), and (b) energetics calculations. In the U.S. Lang inferred dolphin drag during "coast-down" tests (Refs. 52 and 53). This research indicates that during coasting (absence of swimming body motions) the dolphin drag and boundary-layer behavior is nominally what one would expect without any special drag reducing feature. During swimming at lower speeds, the Soviets observe a lower turbulence fluctuation level which they attribute to local pressure gradients induced by the swimming body motion (Ref. 54).

At high speeds the energetics do indicate large apparent drag reductions. As explained by Weihs (Ref. 55), the dolphin, when traveling at high speed, since he has to breathe air anyway, simply "porpoises," i.e., leaps out of the water and thereby reduces his drag <u>force</u> by a factor of 800 (ratio of density of air-to-water). Weihs argued that this more than pays for the interface or wave drag and accounts for the abnormally low apparent drag coefficients inferred from the assumption of fully submerged travel. Further, he argues that body surfing on bow waves accounts for certain near-ship qualitative dolphin speed observations. Therefore, to first order, there evidently is nothing extraordinary with regard to dolphin drag. Controversary remains, however, with respect to the drag-reduction effectiveness of dolphin mucin (Ref. 56).

The status of research concerning the compliant skin effect upon the near-wall flow is that both extensive theory and limited experimental data indicate a correctly designed soft or compliant surface can delay transition from laminar to turbulent flow. There is a lack of experimental replication by independent investigators to bolster scattered claims of apparent compliant wall drag reduction under turbulent flows; alternative explanations have, in fact, been advanced to explain many of the observations.

Behavorial Techniques for Reducing Drag

The "porpoising" or leaping out of the water discussed in the previous section is an obvious example of drag reduction through behavioral modification. Another example analyzed in References 57 and 58 is an alternating gliding and swimming behavior for underwater creatures which lack swim bladders, and therefore must "swim to live;" i.e., to avoid sinking. As the drag while swimming is estimated to be much larger than that while gliding (due largely to drag-due-to-lift/vortex shedding drag), there is a favorable energy benefit in swimming intermittently and maximizing gliding time. Another behavioral modification resulting in drag reduction involves cooperative behavior. The "upwash" associated with drag-due-to-lift from one individual can be utilized by his/her neighbors (while swimming/flying in formation) to ease their propulsion energy requirements (Refs. 59-61). The V-shaped formation of migrating Canadian geese is a typical example.

It should be obvious from the examples of natural drag reduction cited herein that mankind has much to gain from continued study of natural hydro- and aeromechanics.

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SYNOPSIS OF "NATURAL" DRAG REDUCTION TECHNIQUES

1. PRESSURE OR FORM DRAG REDUCTION

   A. SURFACE ROUGHNESS (FLOW "TRIP")
   B. VORTEX GENERATORS (INCL. OWL LEADING EDGE COMB, SHARK DENTICLES, "POP-UP" FEATHERS)
   C. ALULA (LEADING EDGE "SLOT")
   D. CAUDAL FINLETS?
   E. GROOVES
   F. BLOWING (FISH GILLS)
   G. SHARK NOSE FOR VORTEX PRODUCTION
   H. FILLETED/SWEPT INTERSECTIONS
   I. TURNING VANES (FLEXIBLE TRAILING EDGES)
   J. FOLDING/DISAPPEARING FINS
   K. PASSIVE POROUS WALLS?

2. FRICTION DRAG REDUCTION

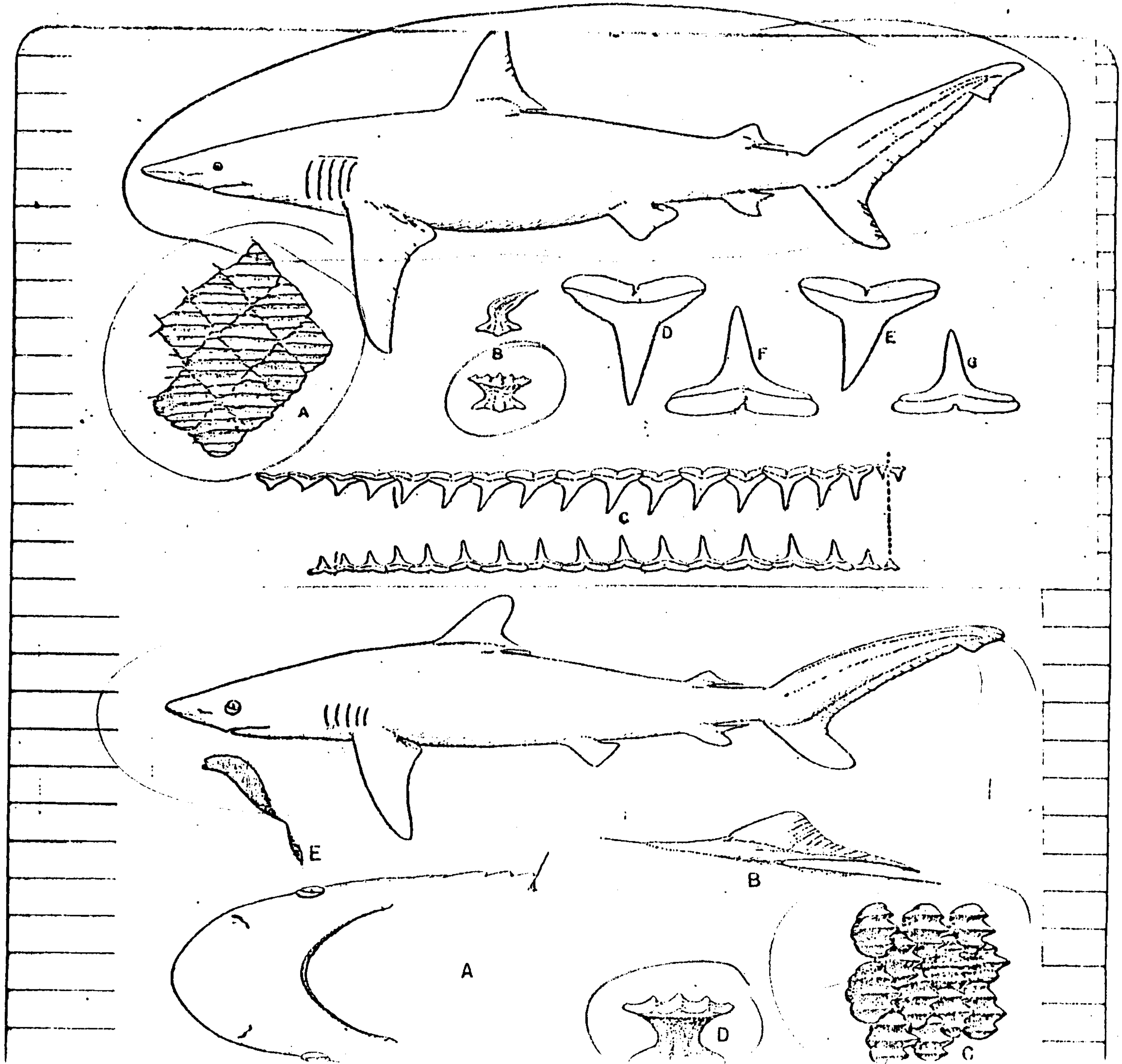
   A. POLYMERS (FISH MUCUS)
   B. SHARK DERMAL DENTICLES/RIBLETS
   C. SWORD FISH ROSTRUM
   D. BUBBLES?
   E. BODY SHAPE/SMOOTHNESS FOR LAMINAR FLOW
   F. ANTI-FOULING COATINGS

3. DRAG-DUE-TO-LIFT-REDUCTION

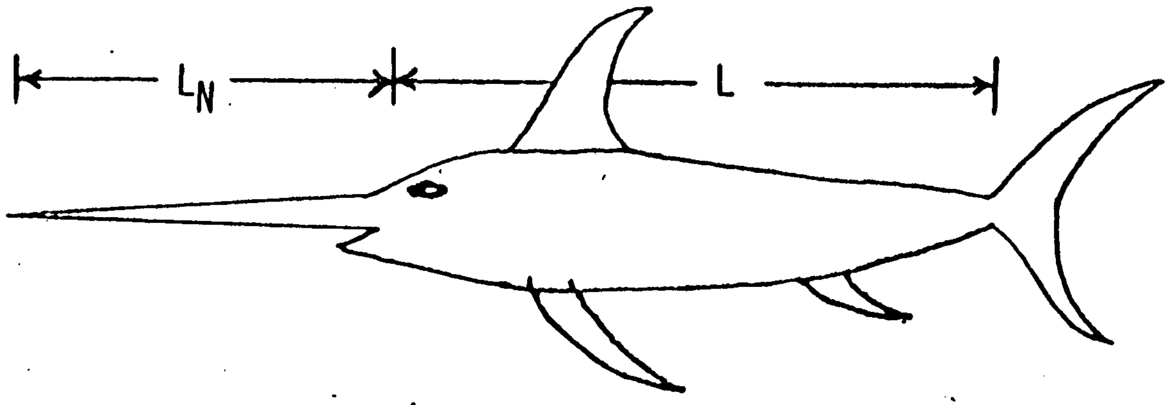
   A. HIGH ASPECT RATIO
   B. SLOTTED TIPS
   C. (NON-PLANAR) UPSWEEP
   D. SWEPT BACK TAPERED TIPS
   E. SERRATED TRAILING EDGES?
   F. FIN RAYS??
   G. LEADING EDGE "BUMPS"??
   H. INDENTED WINGLET (SHARK TIP)

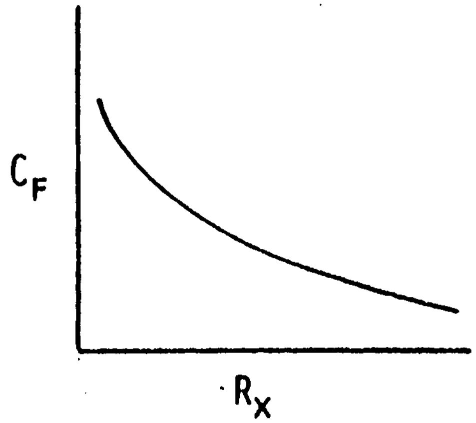
- dermal denticles
=> NASA Riblets

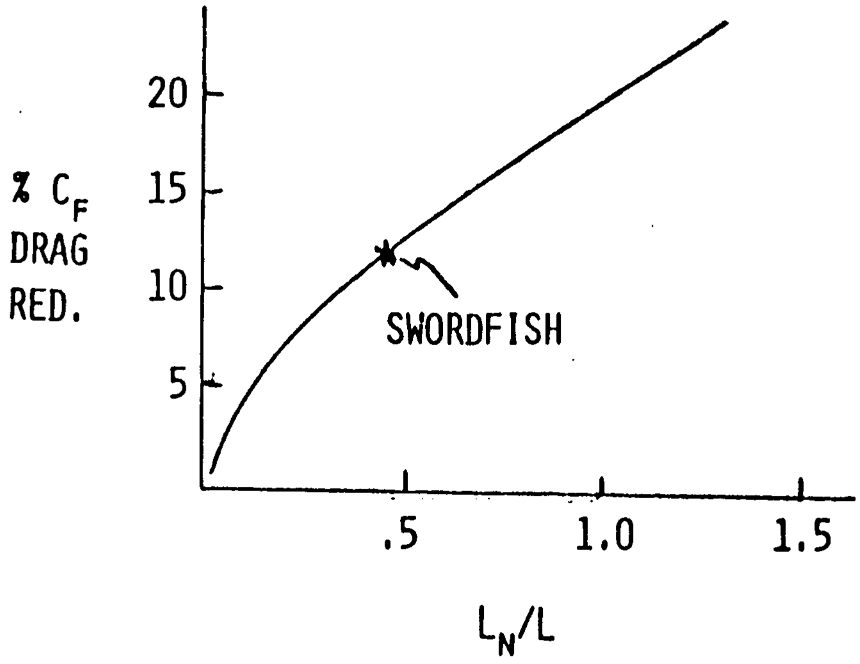
NO



INFLUENCE OF NOSE EXTENSION ON AXIS. BODY DRAG



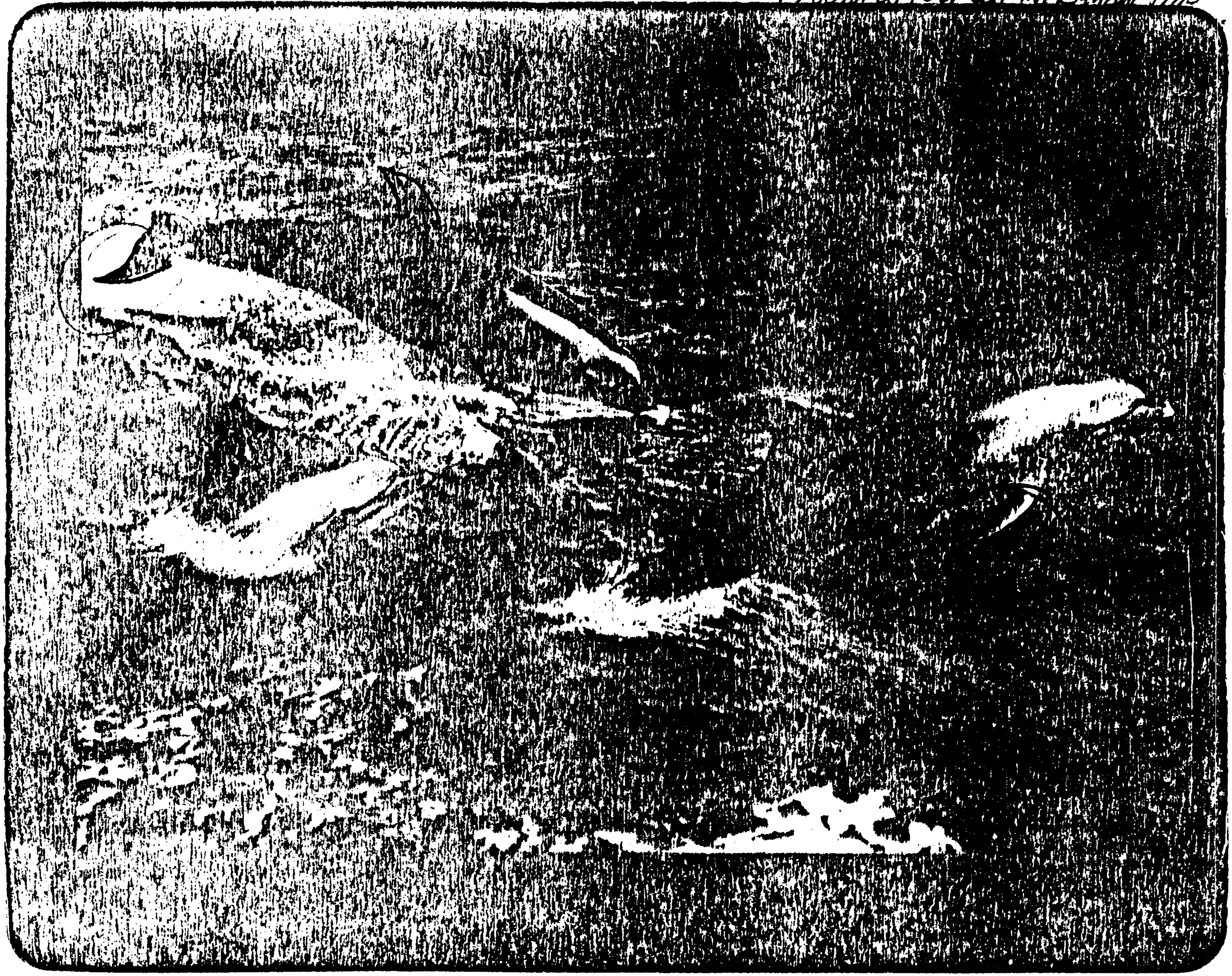




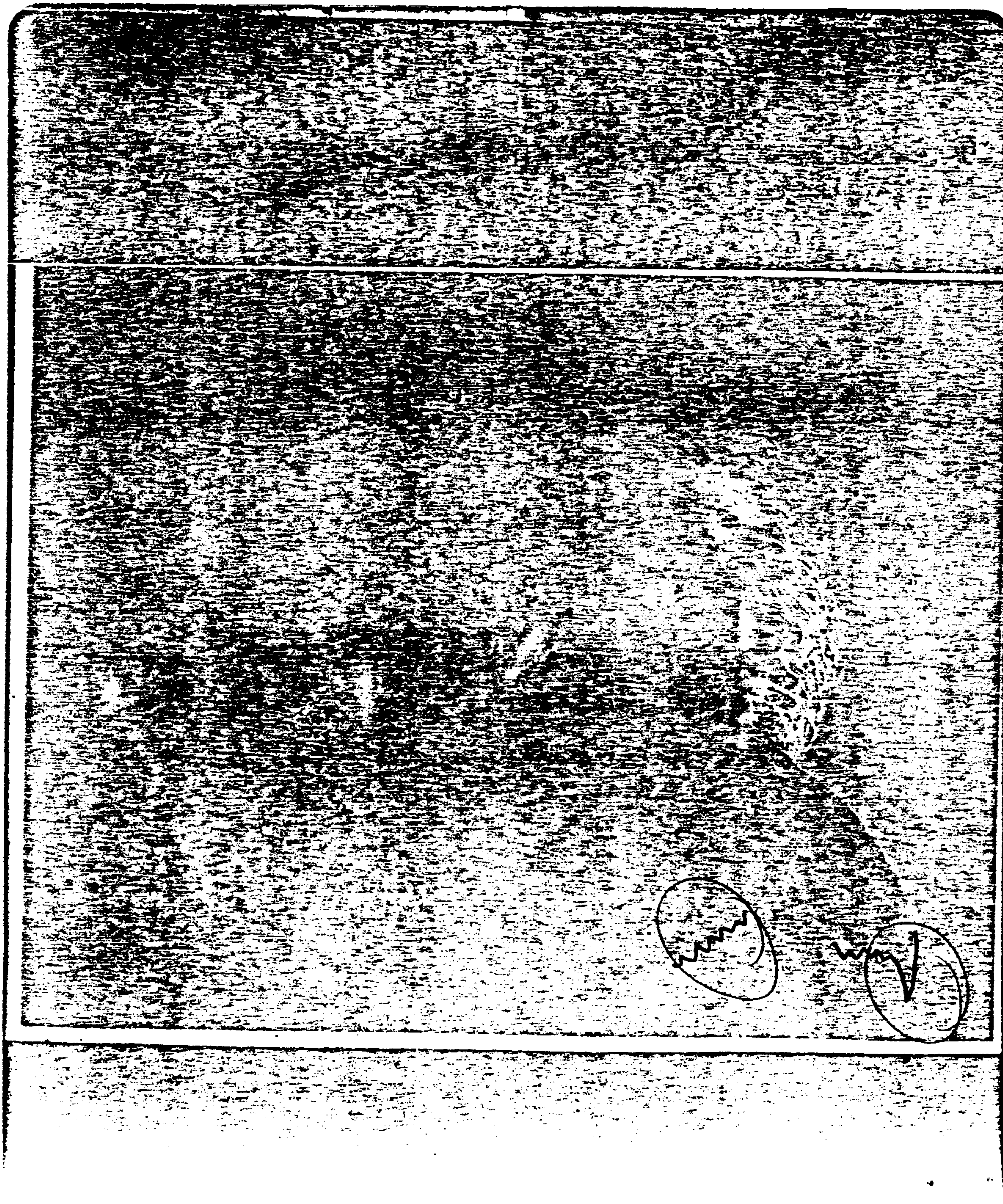
SWORDFISH ROSTRUM

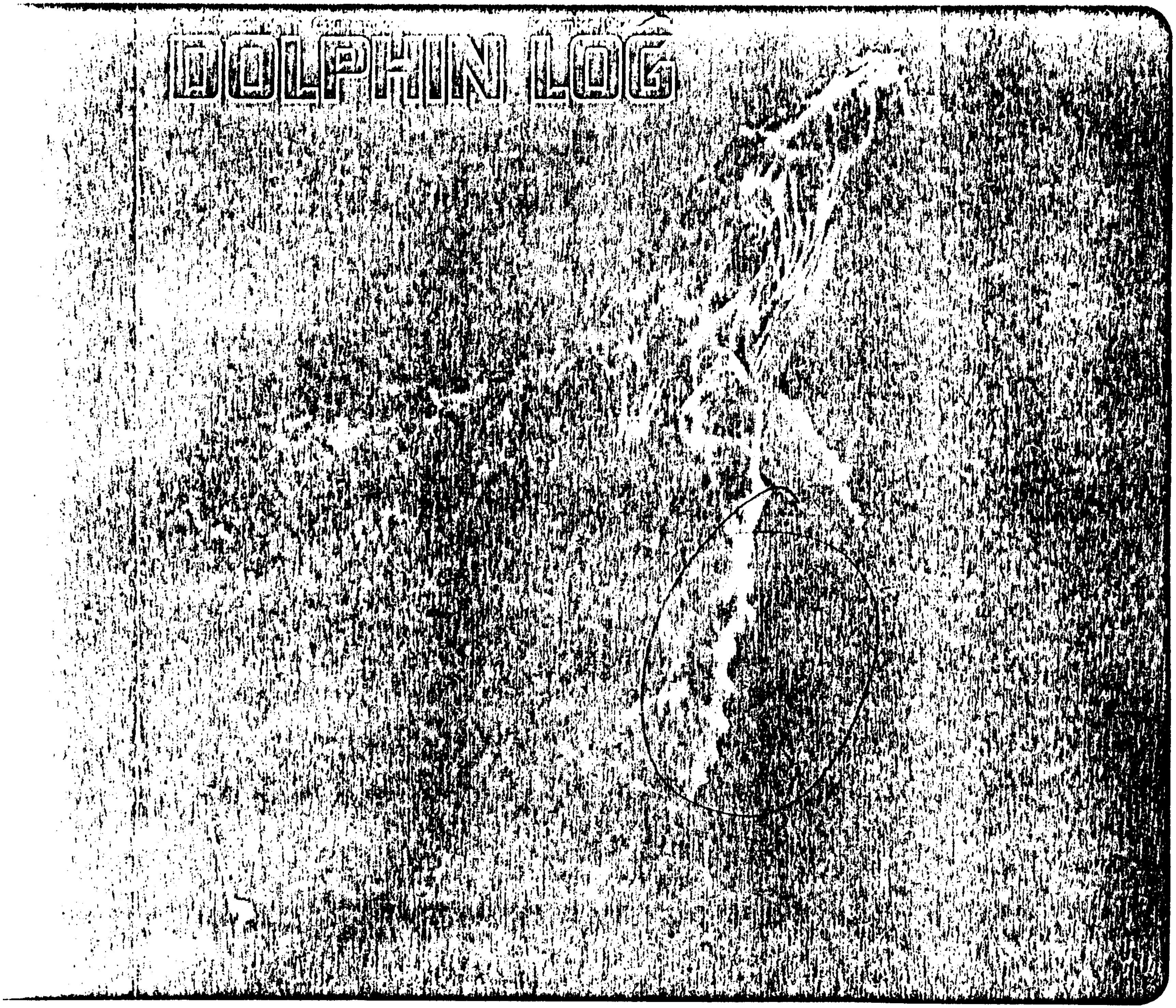
- ROUGHNESS ELEMENTS (PROMOTE TURB.)
- FLATTENED (REDUCE TRANS. CURV. EFFECTS)

Swept back Tapered Tips on
(pectoral, dorsal and caudal fins



Fin back
whale -
swept back
Tapered
Tips and
Serrated
Trailing edge
on Caudal
fin





Leading edge bumps, on pectoral fin of humpback whale